

IRRIGATION IN THE TEXAS HIGH PLAINS: A BRIEF HISTORY AND POTENTIAL REDUCTIONS IN DEMAND[†]

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ABSTRACT

Irrigation for crop production in the semi-arid Texas High Plains is dependent on groundwater withdrawals from the Ogallala Aquifer, which is declining because withdrawals exceed natural recharge. Irrigation development in the region accelerated during the 1950s. Both irrigated area and volume pumped peaked in 1974 and steadily declined during 1974–1989. By 2004, however, irrigated area was nearly the same as it was in 1958, and volume pumped had increased slightly. Several strategies to reduce groundwater withdrawals were reviewed without any reductions in irrigated land area or crop productivity. The most promising evaluated were: (1) increasing weather-based irrigation scheduling using the Texas High Plains Evapotranspiration Network (TXHPET); (2) converting gravity-irrigated land (27% of total) to centre pivot irrigation; and (3) replacing high-water to lower-water demand crops (i.e., corn to cotton). If the land area using the TXHPET network was doubled, and if gravity-irrigated lands were reduced to 10%, groundwater withdrawals could be reduced by 14%. An additional reduction of 8% may be possible by converting half of the irrigated corn area to cotton. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: irrigation; Texas; Ogallala Aquifer; groundwater

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RÉSUMÉ

L'agriculture irriguée dans les hautes plaines semi-arides du Texas dépend des prélèvements d'eaux souterraines dans l'aquifère d'Ogallala, qui baisse parce que les prélèvements excèdent la recharge naturelle. Le développement de l'irrigation dans la région a accéléré pendant les années 50. La surface irriguée et le volume pompé ont atteint leur maximum en 1974 et régulièrement diminué de 1974 à 1989. Cependant en 2004 la surface irriguée était presque la même qu'en 1958 et le volume pompé avait augmenté légèrement. Plusieurs stratégies pour réduire les prélèvements d'eaux souterraines sans réduire la surface irriguée ou diminuer la productivité ont été analysées. Les plus intéressantes sont: (1) augmenter le pilotage de l'irrigation par le réseau de mesure de l'évapotranspiration des hautes plaines du Texas (TXHPET); (2) convertir l'irrigation gravitaire (27% du total) en irrigation par pivot; et (3) remplacer les cultures à forte demande en eau par des cultures à demande plus faible (soit le maïs par le coton). Si la surface utilisant le réseau TXHPET doublait, et si l'irrigation gravitaire était réduite de 10%, les prélèvements d'eaux souterraines pourraient être réduits de 14%. Une réduction complémentaire de 8% serait possible en convertissant la moitié de la surface irriguée de maïs en coton. Copyright © 2008 John Wiley & Sons, Ltd.

MOTS CLÉS: irrigation; Texas; aquifère d'Ogallala; eaux souterraines

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[†]Irrigation dans les hautes plaines du Texas: brève histoire et réductions potentielles de la demande.

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INTRODUCTION

The semi-arid Texas High Plains is a major producer of irrigated and dryland crops and comprises the southern portion of the Great Plains region of the USA. Major irrigated crops include grain corn, upland cotton, grain sorghum, and winter wheat. Minor irrigated crops include peanuts, silage, and soybeans. In the future, irrigated silage area is expected to increase to meet the rapidly expanding dairy market in the region. Irrigation typically results in doubled to quadrupled crop yields compared to dryland production levels, making irrigated agriculture a vital component of the regional economy (Howell, 2001). Large-scale irrigation first became practical in the 1930s–1940s when internal combustion engines, turbine pumps, right-angle gear drives, and rotary well drilling became available for pumping groundwater (Musick *et al.*, 1988). A major drought occurred in the 1950s, which was similar in magnitude to that of the 1930s Dust Bowl; however, widespread crop failure was averted by rapid development of irrigation following World War II (Musick *et al.*, 1990).

Nearly all irrigation in the Texas High Plains was developed solely from the Ogallala (High Plains) Aquifer as surface water resources were inadequate for this purpose. The Ogallala underlies parts of eight states (South Dakota, Nebraska, Wyoming, Colorado, Kansas, Oklahoma, New Mexico, and Texas) and is one of the largest freshwater aquifers in the world. Over 90% of Ogallala withdrawals in the Texas High Plains are for irrigation; however, the Ogallala is essentially a closed basin and withdrawals have greatly exceeded recharge, resulting in a severe decline of groundwater levels since irrigation development began. In some areas, more than 50% of the predevelopment saturated thickness has been pumped, and groundwater levels have dropped over 50 m (McGuire, 2003). The energy required to lift groundwater constitutes a major cost of irrigation, and declining well yield, greater lift requirements, increasing unit energy costs, and relatively static commodity prices led to overall reductions in pumping rates after 1974 (Musick *et al.*, 1990). Consequently, the rate of aquifer decline has abated in some areas. Declining well yields and increases in pumping energy costs will continue to affect upper limits in aquifer withdrawal rates and therefore crop productivity. Furthermore, on September 1, 2005, the 79th Texas Legislature passed House Bill 1763, which requires, among other items, that groundwater management areas establish upper limits for groundwater production (Mace *et al.*, 2006). These factors will significantly impact the long-term economic viability of irrigated agriculture in the Texas High Plains (Taylor *et al.*, 2007).

The purpose of this paper is to (a) briefly review the irrigated area, developments in irrigation technology, and irrigation demand from the Ogallala Aquifer in the Texas High Plains since 1958; (b) review the recent area and productivity for both irrigated and dryland crops to illustrate the relative impact of irrigation, and summarize the irrigation volume applied by crop to illustrate which crops might have the greatest potential impact in reducing total irrigation demand; (c) review several strategies for reducing irrigation demand and their economic feasibility; and (d) estimate the impact on irrigation demand by three of the most promising strategies, which are evapotranspiration (ET)-based irrigation scheduling, converting the remaining gravity-irrigated land to centre pivot, and irrigated crop (corn-to-cotton) conversion.

STUDY AREA

The study area consists of the 39-county area of the Texas Agricultural Statistics Service (TASS) District 11 (Northern High Plains) and District 12 (Southern High Plains), together defined herein as the Texas High Plains (Figure 1). These counties fully or partially overlie the Ogallala Aquifer. The Canadian River roughly divides portions of the Ogallala Aquifer in the Northern District. Elevations above mean sea level (MSL) range from approximately 760 m along the eastern boundaries to over 1200 m toward the northwest. The region is mostly semi-arid, with extremely variable precipitation (both temporally and spatially, averaging 400–560 mm west to east, respectively). The region also has high evaporative demand (approximately 2500 mm yr⁻¹ Class A pan evaporation) due to high solar radiation, high vapor pressure deficit, and strong regional advection. Soils are generally described as moderately permeable in the Southern District, slowly permeable in the Northern District south of the Canadian River, and a mix north of the Canadian River (Musick *et al.*, 1988). Corn and wheat have traditionally been produced north of the Canadian River, while cotton has been produced further south, although cotton has recently expanded northward into the corn-producing areas.

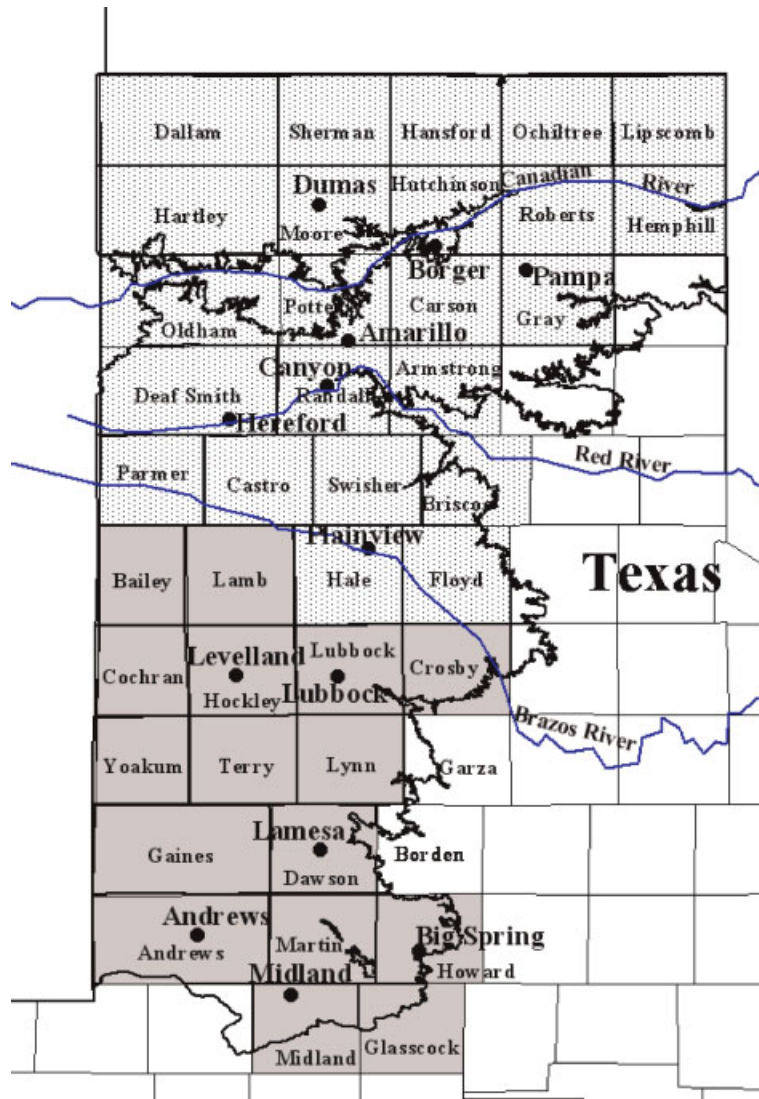


Figure 1. Thirty-nine-county study area of the Texas High Plains, which approximately overlies the Ogallala Aquifer. This figure is available in colour online at www.interscience.wiley.com/journal/ird

IRRIGATED AREA, TECHNOLOGY, AND DEMAND SINCE 1958

Data on irrigated area, technology, and demand estimates were obtained from the Texas Water Development Board (TWDB). The TWDB has conducted irrigation surveys in Texas in cooperation with the Natural Resource Conservation Service and the Texas State Soil and Water Conservation Board since 1958, and has issued reports about every 5 years, with the most recent being in 2000 (Texas Water Development Board, 2001). Irrigated area and demand estimates were also compiled for each county and crop since 1985 (Texas Water Development Board, 2006).

Total irrigated area in 1958 was approximately 1.83 million ha, reaching a peak of 2.42 million ha in 1974, declining to 1.59 million ha in 1989, and increasing to 1.87 million ha by 2000 (Figure 2). In 1958, most land was irrigated using gravity (graded furrow) methods, with only about 11% of the total area being irrigated with sprinklers. Gravity-irrigated land area has decreased continuously since 1974, due to both reduction in total

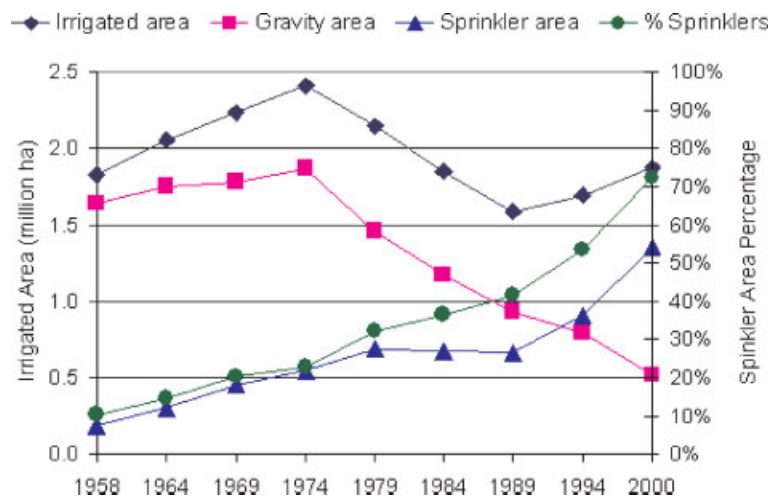


Figure 2. Irrigated area in the Texas High Plains (Texas Water Development Board, 2001). This figure is available in colour online at www.interscience.wiley.com/journal/ird

irrigated land area, and conversion to sprinklers. The relative portion of sprinklers (mainly centre pivots) increased steadily to 1989 and more rapidly thereafter, reaching 72% by 2000. Early sprinklers were impact devices operated at high pressure, but these have been replaced by low-pressure spray since about the early 1980s, and low-energy precision applicators (LEPA; Lyle and Bordovsky, 1983) since the late 1980s, which require less energy (Musick *et al.*, 1988).

Subsurface drip irrigation (SDI) was first adopted by cotton producers in the Southern High Plains and Trans Pecos regions of Texas areas around 1984 (Henggeler, 1995). About 8800 ha of SDI were estimated to be in operation by 2000 (not shown), mainly for cotton production in the Southern High Plains (Texas Water Development Board, 2001). However, some 100 000 ha of SDI were thought to have been installed by 2004, based on informal industry estimates of on-sales and plans submitted to the United States Department of Agriculture Natural Resource Conservation Service (USDA-NRCS) Environmental Quality Incentive Program (EQIP) (J. Bordovsky, pers. comm.). There is evidence that SDI may result in greater crop yield, water use efficiency, and warmer soil temperature (the result of reduced evaporative cooling) relative to spray or LEPA packages on centre pivots (Bordovsky and Porter, 2003; Colaizzi *et al.*, 2004, 2005, 2006). The ability to maintain warmer soil temperatures is critical for early crop establishment and earlier maturity, especially for cotton production in thermally limited environments (Howell *et al.*, 2004). For many producers, this has justified the much greater capital costs and management requirements for SDI relative to centre pivots, particularly in cases where water resources were extremely limited (Bordovsky *et al.*, 2000; Enciso *et al.*, 2005). The rapid adoption of SDI in western Texas was likely in response to intensifying drought, rising energy costs, declining water resources, as well as cost-share incentives such as EQIP, and will likely continue if cotton revenues remain favorable.

The total irrigation volume pumped followed a similar trend as area irrigated, reaching a peak in 1974 and minimum in 1989, and the volume pumped in 2004 (7.4 billion m³) was greater than that pumped in 1958 (6.4 billion m³) (Figure 3). The average irrigation depth varied from 326 mm (1979) to 463 mm (1964), and the average depth applied in 2004 (395 mm) was slightly greater than that estimated for 1958 (348 mm). Depending on where irrigation volumes were measured (i.e., between the well head and field discharge site), the average irrigation depths may include some open channel conveyance and evaporation losses. Most open channels have been replaced by gravity or pressurized pipelines; however, some producers have constructed small open surface reservoirs (which also have evaporative losses) to maintain minimum flows during an irrigation event as well yields decline.

The irrigated area, volume, and average depth applied are influenced by commodity prices, government subsidies, energy costs, rainfall patterns, and conversion to more efficient irrigation systems. The peak of area and volume in 1974 was likely the result of favorable commodity prices and relatively low energy costs of pumping,

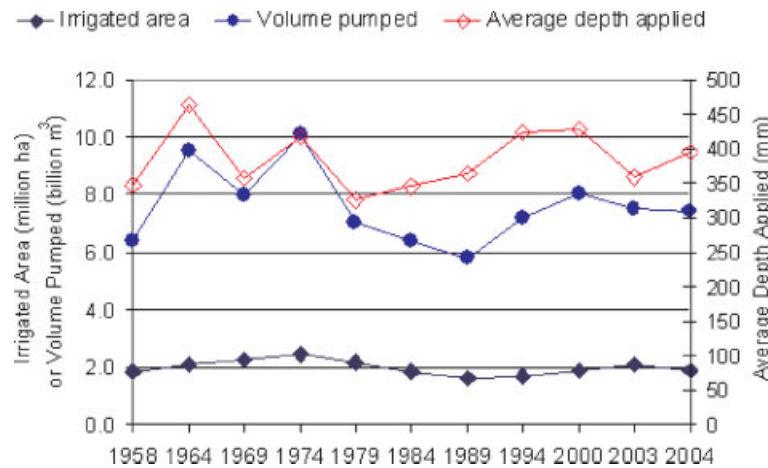


Figure 3. Irrigated area, volume pumped, and average depth applied in the Texas High Plains (Texas Water Development Board, 2001). This figure is available in colour online at www.interscience.wiley.com/journal/ird

followed by steadily increasing energy costs but static or declining commodity prices through 1989 (Musick *et al.*, 1990), and also due to above-average rainfall patterns during the 1980s (Figure 4). Musick *et al.* (1990) anticipated that the irrigated area would continue to decline but at a slower pace in the 1990s, provided commodity and energy prices remained stable. However, both irrigated area (Figure 2) and volume pumped increased from 1989 to 2000, with a smaller increase in average depth applied (Figure 3). This was likely the result of greater local demand for grain by confined animal feeding operations (CAFOs) (Almas *et al.*, 2004). Also, increased adoption of centre pivot systems equipped with low-pressure spray and LEPA packages allowed greater land area to be irrigated with less labor, while newer crop varieties could be adopted that offered greater yield and better resistance to disease and pests. These factors would also require greater production levels (and hence greater irrigation rates) to recoup the investment. Beginning in 2000, the cost of natural gas and other energy sources began to rise, leading to a decrease in irrigation demand (Guerrero *et al.*, 2008); however, this was probably moderated by the onset of a severe drought at the same time (Figure 4). The decline of well yields required an increase in the number of wells to maintain irrigation volumes pumped (Figure 5). In 1958, there were approximately 48 000 wells in the 39-county study area; however, this had more than doubled to 101 000 wells by 2000. The area irrigated per well declined throughout this period. The volume pumped per well declined since 1974, except for a slight increase between 1989 and 1994.

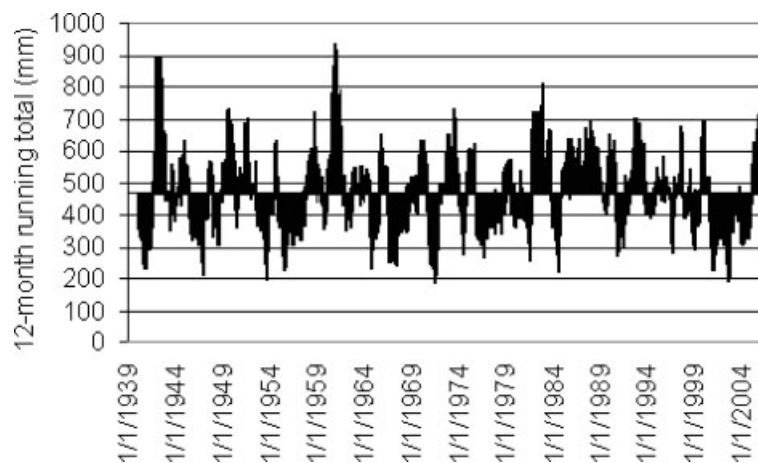


Figure 4. Twelve-month running total precipitation at Bushland, Texas, 1939–2006

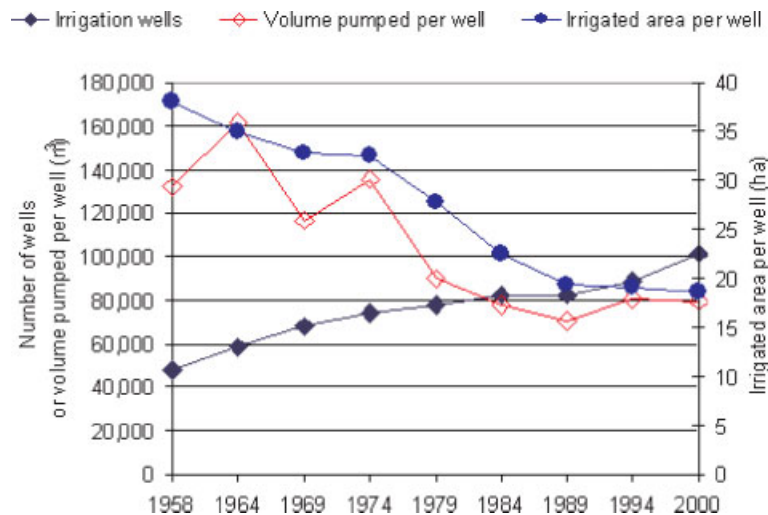


Figure 5. Irrigation wells in the Texas High Plains (Texas Water Development Board, 2001). This figure is available in colour online at www.interscience.wiley.com/journal/ird

AREA, PRODUCTIVITY, AND IRRIGATION DEMAND BY CROP

The recent distribution of cultivated area and productivity for both irrigated and dryland major crops were reviewed to assess the relative impact of irrigation, and the irrigation volume applied by crop were summarized to illustrate which crops might have the greatest potential impact in reducing total irrigation demand. Irrigated area and production data by crop (and corresponding dryland area and production data) were obtained from the United States Department of Agriculture (USDA) National Agricultural Statistics Service (United States Department of Agriculture, 2006). Data were averaged for 1998–2005, and these years were selected to correspond to data available for an analysis of irrigation depths described in a subsequent section. Data were tabulated for the Northern (Table I) and Southern (Table II) High Plains Districts.

In the Northern High Plains (Table I), major irrigated crops were grain corn (26%), cotton (23%), grain sorghum (10%), and winter wheat (30%), where percentages were that of the total irrigated area (1.14 million ha). Minor irrigated crops (11% of total irrigated area) were peanut, soybean, silage, and other crops (alfalfa, barley, oats, pasture, pecans and other orchard, potatoes, sunflower, and vineyard), although silage and forage crops may

Table I. Crop inventory and average yield for the Texas Agricultural Statistics Service (TASS) Northern High Plains District (D11), 1998–2005 averages (United States Department of Agriculture, 2006)

	Dryland area (ha)	Irrigated area (ha)	Percentage crop irrigated (%)	Percentage of total irrigated area (%)	Dryland yield (Mg ha ⁻¹)	Irrigated yield (Mg ha ⁻¹)
Grain corn	497	294 219	100	26	—	11.82
Cotton	71 302	267 109	79	23	0.42	0.88
Grain sorghum	167 356	113 414	40	10	2.29	4.85
Peanut	78	1 081	93	0	—	2.88
Soybean	0	25 149	100	2	—	2.33
Winter wheat	581 702	338 136	37	30	1.64	3.37
Silage	70 293	41 029	37	4	10.57	26.37
Other	37 126	61 080	62	5		
Total	928 353	1 141 216	55			

Table II. Crop inventory and average yield for the Texas Agricultural Statistics Service (TASS) Southern High Plains District (D12), 1998–2005 averages (United States Department of Agriculture, 2006)

	Dryland area (ha)	Irrigated area (ha)	Percentage crop irrigated (%)	Percentage of total irrigated area (%)	Dryland yield (Mg ha ⁻¹)	Irrigated yield (Mg ha ⁻¹)
Grain corn	952	20,273	96	3	—	10.31
Cotton	652,701	502,309	43	65	0.35	0.75
Grain sorghum	173,173	52,890	23	7	1.86	3.56
Peanut	0	69,980	100	9	—	3.97
Soybean	0	4,543	100	1	—	1.68
Winter wheat	118,966	56,920	32	7	1.33	2.56
Silage	30,390	10,663	26	1	3.92	26.43
Other	24,879	49,564	67	6		
Total	1,001,061	767,142	43			

become major irrigated crops in the near future to meet demands by new dairy operations in the area. Irrigated area was 55% of the total area under cultivation, with approximately 0.928 million ha under dryland production. Winter wheat and grain sorghum comprised most of the dryland area, and these crops are sometimes rotated in a wheat–sorghum–fallow rotation over 3 years (Baumhardt *et al.*, 2000). Nearly all grain corn, peanut, and soybean area were irrigated, as these crops have little dryland production potential relative to cotton, grain sorghum, and winter wheat in this region.

In the Southern High Plains (Table II), a similar amount of land was under cultivation, but less area was irrigated (43% of the total). This reflects water resource availability, in that the saturated thickness of the Ogallala decreases toward its southern boundary (McGuire, 2003). About 65% of the total (irrigated plus dryland) cultivated area was for cotton production; similarly, 65% of the total irrigated land was for cotton.

In both the Northern (Table I) and Southern (Table II) High Plains, irrigated crop yields were at least double that of dryland yields. Irrigated and dryland yields averaged for 1998–2005 (where applicable) were slightly greater than 1968–1988 averages reported by Musick *et al.* (1990). The 1968–1988 average yields were 8.34 Mg ha⁻¹ for irrigated grain corn; 0.326 and 0.471 Mg ha⁻¹ for dryland and irrigated cotton, respectively; 1.81 and 5.30 Mg ha⁻¹ for dryland and irrigated grain sorghum, respectively; and 1.18 and 2.74 Mg ha⁻¹ for dryland and irrigated winter wheat, respectively.

Irrigated volume data by crop were obtained from the Texas Water Development Board (2006) and summed for the Northern and Southern High Plains (Table III). In the Northern High Plains, grain corn represented the largest portion of irrigation volume demand (41%), followed by winter wheat (23%) and cotton (18%). In the Southern High Plains, most irrigation water pumped was for cotton (62%). There was considerably greater irrigation water pumped in the Northern High Plains (4.85 billion m³ yr⁻¹) than in the Southern High Plains (3.03 billion m³ yr⁻¹), and this was mainly for grain corn production (1.98 billion m³ yr⁻¹). These differences likely reflect that the Southern High Plains has less available water remaining in the Ogallala Aquifer, but also has greater heat units available, whereby both factors would favor cotton production over corn. Cotton (35%), grain corn (27%), and winter wheat (17%) were the three most irrigated crops (combined total of 79%) for the combined Northern and Southern High Plains; hence, efforts to reduce irrigation applied to these three crops will have the greatest overall impact in reducing withdrawals from the Ogallala Aquifer.

STRATEGIES FOR REDUCING IRRIGATION DEMAND

In 1997, Texas Senate Bill 1 (SB1) established a comprehensive water resource plan for the State of Texas, resulting in 16 planning areas based largely on their unique hydrologic characteristics. The Ogallala Aquifer included areas

Table III. Annual irrigation demand estimates for Northern and Southern High Plains (NHP and SHP, respectively), 1998–2005 averages (Texas Water Development Board, 2006)

	NHP irrigated volume		SHP irrigated volume		NHP + SHP irrigated Volume	
	(billion m ³)	(% of total)	(billion m ³)	(% of total)	(billion m ³)	(% of total)
Grain corn	1.98	41	0.12	4	2.10	27
Cotton	0.86	18	1.89	62	2.75	35
Grain sorghum	0.45	9	0.19	6	0.64	8
Peanut	0.00	0	0.37	12	0.37	5
Soybean	0.09	2	0.02	1	0.11	1
Winter wheat	1.12	23	0.20	7	1.33	17
Forage crops	0.12	3	0.04	1	0.16	2
Other crops	0.22	5	0.21	7	0.42	5
Total	4.85		3.03		7.88	

designated Region A, Region O, and the northern portion of Region F. In Region A (consisting of 21 counties in the Northern Texas Panhandle area), the Agricultural Demands and Projections Committee was formed to estimate present and future (through 2060) water supply and demands and to recommend water conservation strategies to the Panhandle Water Planning Group of Region A. The Agricultural Demands and Projections Committee determined that irrigated crops accounted for 89% of all water use in Region A, and livestock production accounted 3.0% (Amosson *et al.*, 2005, 2006). Irrigation demand was estimated based on methodologies developed by Marek *et al.* (2004).

The Agricultural Demands and Projections Committee identified seven water conservation strategies for irrigated crops, and estimated their potential effectiveness and economic impacts (Amosson *et al.*, 2005). These strategies were: (1) use of the Texas High Plains Evapotranspiration Network for irrigation management; (2) change in crop variety; (3) change in irrigation application technology; (4) change in crop type; (5) conservation tillage methods; (6) precipitation enhancement; and (7) converting marginally irrigated land to dryland production. Each strategy was evaluated on the basis of cumulative water savings, implementation cost, and direct regional economic impact (i.e., change in gross crop receipts) over the 60-year planning horizon (Table IV).

Crop variety changes (long- to short-season grain corn and grain sorghum), change in high-water use crops (grain corn) to lower-water use crops (grain sorghum, soybean, and cotton), and conversion of marginally irrigated lands to dryland production (cotton, grain sorghum, and winter wheat) offered the greatest water savings (20% total), but all had very negative economic impacts (Table IV). Because of the semi-arid climate, any substantial conversion from irrigated to dryland cropping systems would have severe economic consequences (Almas *et al.*, 2006) unless alternative economic activities could be developed that were not dependent on intensive pumping from the Ogallala (Almas *et al.*, 2004).

The remaining strategies as identified by the Agricultural Demands and Projections Committee did not offer as large potential water savings (13% total), and although economic impacts were not quantified these impacts were anticipated to be either neutral or positive (Table IV). Several precipitation enhancement programs were conducted by groundwater management districts in the Texas High Plains in recent years (Almas, 2005); however, these have been discontinued, and it is uncertain whether these will be reinstated in the future.

Conservation tillage was estimated as having the least implementation cost (and least implementation cost per water savings) (Table IV); this cost was due to increased herbicide applications but did not include equipment purchases or modification. Conservation tillage may increase available soil moisture by 25 mm or more around planting time compared with conventional tillage methods in several Texas High Plains soils (Johnson, 1964; Unger, 1984; Zhai *et al.*, 1990; Unger and Cassel, 1991; Weise *et al.*, 1998; Moroke *et al.*, 2005). In 2000, approximately 50% of irrigated land in Region A was under some form of conservation tillage as defined by the Conservation and Technology Center at Purdue University (Simpson, 2005). Assuming that a 25 mm reduction in irrigation water applied is valid for all crops in the Northern and Southern High Plains, each 10% increase in

Table IV. Water conservation strategies and their impacts as analyzed by Amosson *et al.* (2005)

Irrigation demand reduction strategy	Cumulative water savings (WS) (billion m ³)	WS/total irrigation demand (%)	Implementation cost (IC) (million US \$)	IC/WS (million US \$/billion m ³)	Direct regional economic impact (DREI) (million US \$)	DREI/WS (million US \$/billion m ³)
1. Irrigation management using TXHPET Network	2.55	1.96	8.1	3.18	+	+
2. Change in crop variety	8.22	6.32	*	*	−1549	−188.41
3. Change in irrigation application technology	5.09	3.91	US \$169.6	33.31	*	*
4. Change in crop type	10.75	8.26	46.0	4.28	−2054	−191.04
5. Conservation tillage methods	2.64	3.02	1.1	0.42	*	*
6. Precipitation enhancement	5.07	3.89	25.8	5.09	+	+
7. Convert marginally irrigated land to dryland production.	6.37	4.89	39.0	6.13	−406	−63.77

*, Not quantified; +, not quantified but was anticipated to be positive.

irrigated area under conservation tillage would result in a 1.0% reduction in irrigation demand (or 3.0% for an 80% adoption rate, similar to Table IV which applied to Region A only).

The Texas High Plains Evapotranspiration Network includes 17 dedicated agricultural meteorological stations at strategic locations in the Northern and Southern High Plains (Howell *et al.*, 1998a; Porter *et al.*, 2005). Crop evapotranspiration (ET_c) and other pertinent crop information are compiled into a single page (Figure 6) and disseminated daily to producers, crop consultants, extension personnel, and others by facsimile, email list-serve, and Internet downloads. Potential water savings using the Texas High Plains Evapotranspiration Network (Table IV) were based on assuming a uniform 25 mm reduction in applied irrigation for all crops, with assumed adoption rates of 10% of total irrigated land in 2000, 20% by 2010, and 7.5% increases per decade thereafter, reaching 50% by 2050 (Gaskins and Jones, 2005). Potential water savings through conversion to more efficient irrigation systems were based on assumed, fixed application efficiencies, with adoption rates reflecting historic observations (Simpson and Gaskins, 2005). Although changing irrigation technology was estimated as having by far the greatest implementation cost (Table IV), some costs may be offset by cost-share programs, reduced labour, reduced agrochemical requirements, and greater crop productivity. Furthermore, producers continue to embrace more efficient irrigation systems throughout the US Great Plains, and some groundwater conservation districts have initiated phasing out all remaining gravity irrigation systems.

Recent irrigation management data from the Texas Cooperative Extension Agri-Partners Program reflect actual producer behavior using the Texas High Plains Evapotranspiration Network and various irrigation systems (graded furrow, centre pivot, and SDI; New, 2006). Hence, irrigation demand computed based on Agri-Partners data in comparison with Texas Water Development Board data (Table III) may offer more refined estimates of potential water savings through adoption of the Texas High Plains Evapotranspiration Network and irrigation technology changes. An additional strategy includes replacing a portion of the irrigated corn area with cotton only (excluding soybeans and grain sorghum as analyzed by the Agricultural Demands and Projection Committee). Conversion from corn to cotton has been successfully implemented in the Northern High Plains and Southwestern Kansas. Potential water savings under each of these strategies (increased adoption of Texas High Plains Evapotranspiration Network, irrigation technology, and corn-to-cotton conversion), without decreasing total irrigated area or crop productivity, were computed for the 39-county study area in the Northern and Southern High Plains (Figure 1) as described in the following sections.

North Plains ET Network Weather Station, Bushland (ARS), TX

Temperatures (F)													
Date	ETo	---Air---		Soil Min		Prec.	Growing		Degrees		Days (F)		
	in.	Max	Min	2in.	6in.	in.	Crn	Srg	Pnt	Cot	Soy	Wht	
06/13/98	.42	93	58	64	70	0.00	22	25	0	15	26	37	
06/14/98	.31	87	52	63	69	0.00	19	20	0	10	23	34	
06/15/98	.26	78	53	65	70	0.00	15	15	0	5	19	33	
10-day avg min soil temp							63	68	Wind	9.8	mph from	11 deg.	
CORN													
Seed	Acc	Short Season Var.		Water Use			Long Season Var.		Water Use				
Date	GDD	Growth	Day	3day	7day	Seas.	Growth	Day	3day	7day	Seas.		
		Stage	-----in/d-----			in.	Stage	-----in/d-----			in.		
04/01	1090	10-leaf	.30	.38	.34	11.3	10-leaf	.30	.38	.34	11.3		
04/15	955	8-leaf	.26	.33	.29	8.7	8-leaf	.26	.33	.29	8.7		
05/01	831	6-leaf	.22	.28	.26	6.6	6-leaf	.22	.28	.26	6.6		
05/15	622	4-leaf	.18	.23	.19	3.9	4-leaf	.18	.23	.19	3.9		
SORGHUM													
Seed	Acc	Short Season Var.		Water Use			Long Season Var.		Water Use				
Date	GDD	Growth	Day	3day	7day	Seas.	Growth	Day	3day	7day	Seas.		
		Stage	-----in/d-----			in.	Stage	-----in/d-----			in.		
05/01	890	5-leaf	.18	.23	.21	6.7	4-leaf	.16	.20	.18	6.3		
05/15	678	5-leaf	.18	.21	.18	4.4	4-leaf	.16	.20	.18	4.4		
06/01	279	Emerged	.10	.13	.12	1.7	Emerged	.10	.13	.12	1.7		
06/15	15	Seeded	.10	.15	.16	0.1	Seeded	.10	.15	.17	0.1		
COTTON													
Seed	Acc	North Plains Area		Water Use			South Plains Area		Water Use				
Date	GDD	Growth	Day	3day	7day	Seas.	Growth	Day	3day	7day	Seas.		
		Stage	-----in/d-----			in.	Stage	-----in/d-----			in.		
05/01	398	Emerged	.13	.17	.15	4.6	Emerged	.13	.17	.15	4.6		
05/15	352	Emerged	.13	.17	.15	3.6	Emerged	.13	.17	.15	3.6		
06/01	128	Emerged	.13	.07	.05	0.6	Emerged	.13	.07	.05	0.6		
06/15	5	Seeded	.03	.13	.16	0.0	Seeded	.03	.13	.16	0.0		
SOYBEANS													
Seed	Acc	Late Group 4-Var.		Water Use									
Date	GDD	Growth	Day	3day	7day	Seas.							
		Stage	-----in/d-----			in.							
05/15	742	V-2	.18	.22	.19	5.3							
06/01	316	Emerged	.14	.18	.16	1.9							
06/15	19	Seeded	.10	.08	.08	0.1							
WHEAT													
Seed	Acc			Water Use									
Date	GDD	Growth	Day	3day	7day	Seas.							
		Stage	-----in/d-----			in.							
08/15	6283	H Dough	.13	.17	.18	31.3							
09/10	5282	H Dough	.13	.19	.18	27.8							
10/01	4562	H Dough	.13	.19	.18	26.5							
10/15	4117	H Dough	.13	.20	.19	25.0							
Fescue/Bluegrass lawn water use 0.26 inch													
Bermuda grass lawn water use 0.19 inch													
Buffalo grass lawn water use 0.13 inch													

Figure 6. Example of Texas High Plains Evapotranspiration Network single-page facsimile

ET-BASED IRRIGATION SCHEDULING AND IRRIGATION TECHNOLOGY

The potential impact of ET-based irrigation scheduling was estimated by computing irrigation demand volumes for varying portions of irrigated area either managed or not managed by the Texas High Plains Evapotranspiration Network (Howell *et al.*, 1998a; Porter *et al.*, 2005). These estimates were combined with varying portions of irrigated area with either gravity or centre pivot.

For a specific crop, the total annual irrigation demand volume (V) in the 39-county Study Area (Figure 1) may be computed as:

$$V = \sum_{i=1}^{39} I_{d,i} A_i \quad (1)$$

where I_d is the irrigation depth applied to the crop, A is the irrigated area of the crop, and i is the county. The irrigation depth I_d depends on both producer management strategies and climatic variability, expressed as:

$$I_d = \text{FIR} \cdot I_{\text{req}} \quad (2)$$

where I_{req} is the seasonal net irrigation requirement, and FIR is defined as the fraction of I_{req} and accounts for deficit irrigation ($\text{FIR} < 1.0$) or excessive irrigation ($\text{FIR} > 1.0$). As described shortly, FIR was the basis for comparing irrigation demand for crops managed with or without the Texas High Plains Evapotranspiration Network using gravity or centre pivot.

For each crop, county, and growing season, I_{req} was computed as:

$$I_{\text{req}} = \max \left\{ \left[\sum_{j=1}^n (\text{ET}_{c,j} - P_j) \right], \left[\sum_{j=1}^n (\text{ET}_{c,j-1} - P_{j-1}) \right] \right\} \quad (3)$$

where ET_c is the crop evapotranspiration, P is precipitation, and n is the number of days in an irrigation season. In Equation (3), the cumulative difference between ET_c and precipitation on day j (P_j) were compared to the previous day ($j - 1$), taking the larger value for I_{req} on day j . This approach provided more realistic I_{req} values than assuming $I_{\text{req}} = \sum_{j=1}^n (\text{ET}_{c,j} - P_j)$ because it accounts for soil water deficits that have already occurred prior to large precipitation events, especially late in the season. Irrigation seasons were initiated at planting, which were assumed to occur when average 5-day soil temperatures at 5 cm depth were greater than the crop baseline temperature (minimum temperature required for growing degree day (GDD) or heat unit accumulation), and after a minimum planting date (Table V). Irrigations were assumed terminated (on day n) when the crop was at or near completion of its reproductive stage (shown as GDD in Table V). For cotton, which has indeterminate reproductive stages, termination was assumed to occur when bolls were 25% open. The I_{req} on the day of irrigation termination was the I_{req} used for the crop season.

ET_c was computed as the product of grass reference ET and a crop coefficient:

$$\text{ET}_c = \text{ET}_{\text{os}} \cdot K_{\text{co}} \quad (4)$$

where ET_{os} is the newly standardized ASCE Standardized Penman–Monteith equation using a short vegetation (grass) reference (Allen *et al.*, 2005), and K_{co} is the crop coefficient, which reflects both transpiration and evaporation under fully irrigated conditions. The K_{co} functions were developed at the United States Department of Agriculture–Agricultural Research Service (USDA-ARS) Conservation and Production Research Laboratory in Bushland, Texas, where large precision weighing lysimeters have measured water use of major irrigated crops in the region since 1987 (Evelt *et al.*, 2000; Howell *et al.*, 1995, 1997, 1998b, 2004; Steiner *et al.*, 1991). The K_{co} functions are based on cumulative growing degree days (GDD) computed using crop-specific minimum and maximum air temperature thresholds (although cotton had no maximum) (Table V). The Texas High Plains Evapotranspiration Network provided meteorological data required for computing ET_{os} and K_{co} .

The fraction of the seasonal net irrigation requirement (FIR) was the basis for estimating the impact of the Texas High Plains Evapotranspiration Network and choice of irrigation technology. FIR was estimated based on irrigated

Table V. Crop parameters used to estimate net irrigation requirements (Porter *et al.*, 2005)

	Minimum plant date	Baseline temperature (°C)	Peak temperature (°C)	Growing degree days at irrigation termination (°C)	Minimum growing degree days at harvest (°C)
Grain corn	15 April	10.0	30.0	1530	1890
Cotton	15 May	15.6	(no peak)	930	1080
Grain sorghum	15 May	10.0	37.8	1230	1830
Peanut	1 May	12.8	35.0	1250	1510
Soybean	1 June	7.8	30.0	1780	1890
Winter wheat	1 September	0.0	26.1	2470	2970

Table VI. Applied irrigation depths, fraction of net irrigation requirement (FIR), and crop yield for Texas Cooperative Extension Agri-Partners Program (New, 2006) and Texas High Plains (Texas Water Development Board, 2006), 1998–2005 averages

	Agri-Partners ^a				Agri-Partners ^a				Agri-Partners ^a		
	SDI <i>I_d</i> (mm)	CP <i>I_d</i> (mm)	Grav. <i>I_d</i> (mm)	TWDB <i>I_d</i> (mm)	SDI FIR	CP FIR	Grav. FIR	TWDB FIR	SDI Yield (Mg ha ⁻¹)	CP Yield (Mg ha ⁻¹)	Grav. Yield (Mg ha ⁻¹)
Grain corn	—	538	745	667	—	0.86	1.15	1.18	—	11.96	10.69
Cotton	274	274	194	357	1.01	1.03	0.56	1.28	1.48	1.17	0.67
Grain sorghum	—	290	374	382	—	0.87	1.40	1.15	—	6.61	8.11
Peanut	—	440	—	524	—	1.40	—	1.36	—	4.37	—
Soybean	—	361	380	372	—	0.75	0.99	0.77	—	3.83	3.16
Winter wheat	—	202	221	335	—	0.57	0.57	0.81	—	4.44	4.64

^aSDI, subsurface drip irrigation; CP, centre pivot, and includes impact, spray, and low-energy precision applicator (LEPA); Grav., gravity (surface) irrigation, mainly graded furrow.

area known to have been managed by the Texas High Plains Evapotranspiration Network under the Texas Cooperative Extension Agri-Partners Program (New, 2006). FIR was also estimated using Texas Water Development Board data (Table III), which includes area managed both with and without the Texas High Plains Evapotranspiration Network:

$$\begin{aligned}
 \text{FIR}_{\text{AP,G}} &= \frac{I_{\text{d,AP,G}}}{I_{\text{req}}} \\
 \text{FIR}_{\text{AP,CP}} &= \frac{I_{\text{d,AP,CP}}}{I_{\text{req}}} \\
 \text{FIR}_{\text{AP,SDI}} &= \frac{I_{\text{d,AP,SDI}}}{I_{\text{req}}} \\
 \text{FIR}_{\text{TWDB}} &= \frac{V}{I_{\text{req}}A}
 \end{aligned} \tag{5}$$

where the subscript AP is Agri-Partners, TWDB is Texas Water Development Board, G is gravity irrigation, CP is centre pivot irrigation, SDI is subsurface drip irrigation, and all terms are as defined previously. The Agri-Partners program includes irrigation management demonstrations on commercial farms throughout the Northern High Plains, where irrigations were metered based on crop evapotranspiration (ET_c), local precipitation, and qualitative assessment of near-surface soil moisture using gypsum blocks. The irrigation management component of Agri-Partners has been conducted since 1998, and by 2005 the sample size had grown to approximately 20 000 ha on 450 individually managed fields and included most of the crops (both irrigated and dryland) and irrigation technology (G, CP, SDI) common in the region. Irrigation demand volumes for each type of irrigation technology by crop were not available from the Texas Water Development Board.

The FIR of each crop was computed using Equation (5), which reflected weighted averages of each county and growing season (Table VI). The FIR of most crops under the Agri-Partners program were similar to or less than unity, except for peanut irrigated by centre pivot and corn and sorghum irrigated by gravity. The greater FIR for peanut (1.40) resulted because the soil surface must be maintained in a relatively moist condition during the pegging stage, and this is not accounted for in K_{co} . The small FIR for cotton under gravity irrigation (0.57) relative to centre pivot (1.03) may have reflected the different goals of maximizing water value versus lint yield (e.g., Bordovsky *et al.*, 2006) for gravity and centre pivot, respectively (i.e., limited water resources were allocated to a greater land area under gravity, but concentrated on a smaller land area to recoup the investment on a centre pivot). The FIR for all crops estimated by Texas Water Development Board data were greater than unity (except for

soybean and winter wheat). Grain yield response of winter wheat greatly diminishes for FIR greater than 0.50 (Schneider and Howell, 1997, 2001); hence the FIR of 0.57 for both gravity and centre pivot was probably close to optimal for maximum water use efficiency.

Centre pivot irrigation usually resulted in greater crop yields, except for grain sorghum and winter wheat; grain sorghum had greater FIR under gravity irrigation (Table VI). Cotton lint yield was greater with subsurface drip irrigation than centre pivot, although FIR was similar. Crop yields of Agri-Partner co-operators were generally greater than those reported by the United States Department of Agriculture (2006) in the Northern High Plains (Table I). This may have reflected a greater level of crop management inherent with Agri-Partner co-operators, but also possibly because the United States Department of Agriculture (2006) data probably included a greater number of fields damaged by pests, disease, and unfavorable weather conditions (large hail, prolonged high wind, and very sudden temperature extremes are common throughout the USA Great Plains). Also, winter wheat yields reported by the United States Department of Agriculture (2006) may also have included fields that were both grazed and harvested for grain.

Noting that FIR_{AP} was generally less FIR_{TWDB} , and noting that crop yield under Agri-Partners was seldom reduced when FIR was reduced, suggests that Ogallala withdrawals could be reduced without decreasing crop productivity in the Texas High Plains by greater adoption of the Texas High Plains Evapotranspiration Network. Additional reductions may be realized by converting the remaining gravity-irrigated land to a more advanced irrigation system technology (i.e., centre pivot or subsurface drip). This was investigated by re-expressing FIR_{TWDB} as:

$$FIR_{TWDB} = \tau(\phi_{SDI}FIR_{AP,SDI} + \phi_{CP}FIR_{AP,CP} + \phi_GFIR_{AP,G}) + (1 - \tau)(FIR_{\notin AP}) \quad (6)$$

where τ is the fraction of irrigated land managed or in some way influenced by the Texas High Plains Evapotranspiration Network, $FIR_{\notin AP}$ reflects irrigated land not managed with the Texas High Plains Evapotranspiration Network, and all other terms are as defined previously. Present estimates of τ are 30–40% based on the number of Texas High Plains Evapotranspiration Network subscribers and corresponding irrigated land managed (Marek *et al.*, 2005; T. A. Howell and R. N. Clark, pers. comms), which is greater than adoption rates assumed by the Agricultural Demand and Projection Committee (Gaskins and Jones, 2005). Assuming $\tau = 40\%$ (giving a more conservative estimate of $1 - \tau = 60\%$), $\phi_{CP} = 72\%$, and that ϕ_{SDI} is negligible (resulting in $\phi_G = 1 - \phi_{CP}$), $FIR_{\notin AP}$ was estimated for each crop from Equation (6). Next, τ and ϕ_{CP} were varied as:

$$\begin{aligned} 40\% &\leq \tau \leq 100\% \\ 72\% &\leq \phi_{CP} \leq 100\% \end{aligned}$$

to give new FIR_{TWDB} values for each crop, and resulting irrigation demand volumes were obtained by Equations (2) and (1).

Irrigation demand volumes for the Northern and Southern High Plains, as well as combined totals, had near-linear responses, even though τ and ϕ_{CP} were varied simultaneously (Figure 7). Little response was observed for ϕ_{CP} because the smaller $FIR_{AP,G}$ for cotton (0.56) relative to $FIR_{AP,CP}$ (1.03) compensated for other crops where $FIR_{AP,G} > FIR_{AP,CP}$; furthermore, $FIR_{AP,G}$ and $FIR_{AP,CP}$ were equal (0.57) for winter wheat.

Most response in irrigation demand was due to τ . If τ was doubled (i.e., from 40% to 80%), and if ϕ_{CP} was increased to 90%, total irrigation demand might be reduced by 1 billion $m^3 yr^{-1}$, or a 14% water and energy savings. Up to 21% water and energy savings might be realized if the Texas High Plains Evapotranspiration Network was used for irrigation management on all land presently irrigated in the Northern and Southern High Plains.

CORN TO COTTON CONVERSION IN THE NORTHERN HIGH PLAINS

Cotton production has recently expanded northward into areas where corn was traditionally produced in the Northern Texas High Plains. The northern extent of cotton production was limited to the area around Hereford, Texas (Figure 1) until 1998, thereafter expanding to southwestern Kansas. Both crops have had similar revenue potential in recent years, but maximum cotton yields are possible with about half the irrigation relative to corn; furthermore, profitable cotton yields are possible with limited (deficit) irrigation, unlike corn (Schneider and

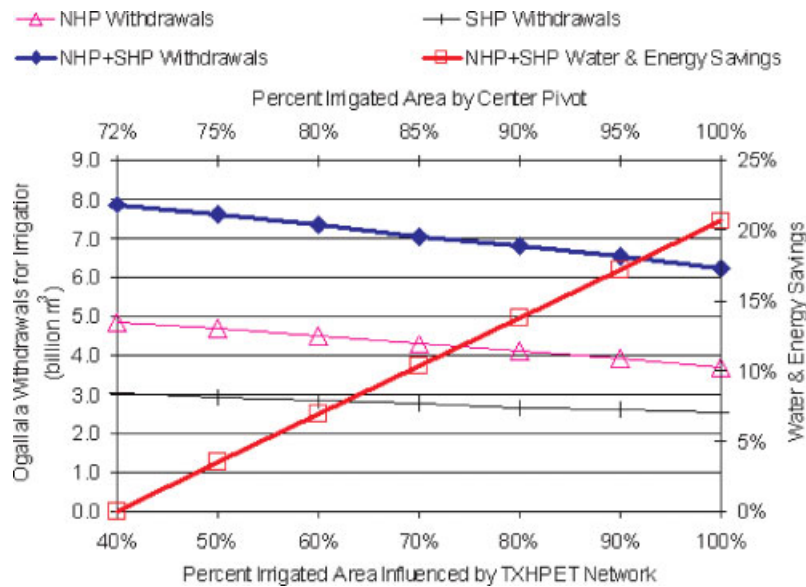


Figure 7. Estimates of withdrawals from the Ogallala Aquifer for irrigation in the Northern High Plains (NHP) and Southern High Plains (SHP). This figure is available in colour online at www.interscience.wiley.com/journal/ird

Howell, 1998; Howell *et al.*, 2004; Almas *et al.*, 2007). Although it appears recent cotton varieties require less heat units to reach adequate maturity, there is still inherent risk in producing cotton in a thermally limited climate. Esparza *et al.* (2007) computed probabilities of accumulated heat units for cotton (15.6°C base temperature) for the 131 counties overlying the Ogallala Aquifer in Colorado, Kansas, New Mexico, Oklahoma, and Texas. They reported that 110 counties received at least 1000 (°C) heat units in 3 out of 4 years. Gowda *et al.* (2007) estimated that 91 of the 110 counties in the same study area had cotton lint yield potentials of at least 500 kg ha⁻¹ in 3 out of 4 years. They estimated a potential reduction in irrigation demand of 0.465 billion m³ yr⁻¹, if 50% of the corn area was converted to cotton in these counties (250 000 ha), with no other changes in irrigation management strategies or irrigation technology. Of course, additional water savings could be realized with deficit irrigation (i.e., 0 < FIR < 1), provided reductions in yield could be offset by reduced input costs of irrigation so as to maintain farm profitability.

Annual irrigation demand of cotton and corn was estimated in the Northern High Plains (23 counties) for irrigated corn-to-cotton area conversions from 0 to 100%, and for various portions of total land area (τ) influenced by the Texas High Plains Evapotranspiration Network (40%, 60%, 80%, and 100%) as:

$$V_{\text{CORN}} = \text{FIR}_{\text{TWBB,CORN}} \left[\sum_{i=1}^{23} I_{\text{req,CORN},i} A_{\text{CORN},i} (1 - \kappa) \right] \quad (7)$$

$$V_{\text{COTTON}} = \text{FIR}_{\text{TWBB,COTTON}} \left[\sum_{i=1}^{23} I_{\text{req,COTTON},i} (A_{\text{COTTON},i} - A_{\text{CORN},i} \kappa) \right] \quad (8)$$

where κ is the percentage of irrigated corn area converted to irrigated cotton, and all other terms are as defined previously. No additional changes in conversion from gravity to centre pivot irrigation were assumed, and no estimates were made for the Southern High Plains as relatively little grain corn is produced there. Annual irrigation demands for all other crops were added to V_{CORN} and V_{COTTON} to determine the total irrigation demand volume for the Northern High Plains (Figure 8). If $\kappa = 50\%$ of the corn area was converted to cotton, and assuming τ remained at 40%, Ogallala withdrawals might be reduced by 0.65 billion m³ yr⁻¹. An additional 0.63 billion m³ yr⁻¹ might be

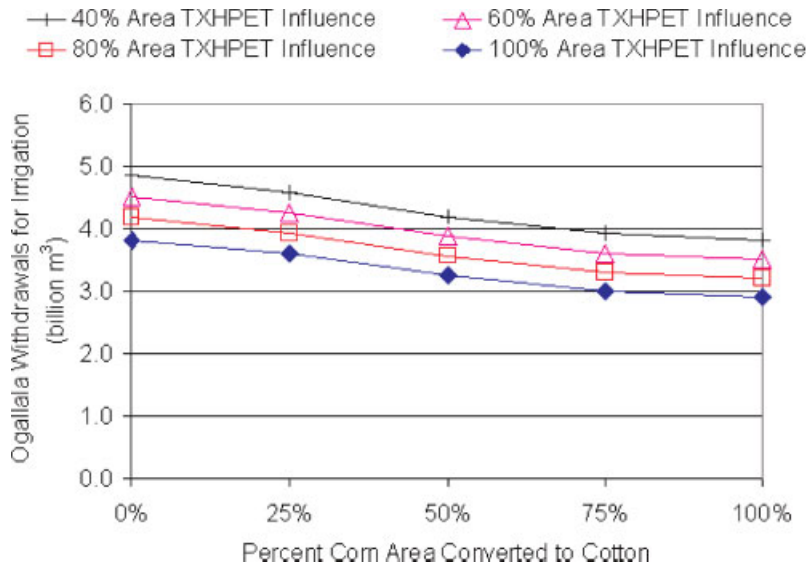


Figure 8. Estimates of withdrawals from the Ogallala Aquifer for irrigation in the Northern High Plains (NHP) for corn area converted to cotton. This figure is available in colour online at www.interscience.wiley.com/journal/ird

possible by increasing τ to 80%. It is highly improbable that cotton will completely replace corn in the near future, given the growing regional demand for corn by confined animal feeding operations (CAFO), coupled with volatile global cotton markets, and the greater risk of producing cotton in a climate having marginal heat units. Furthermore, the rapidly growing demand for ethanol feedstock may temporarily result in much greater revenue potential for corn compared with cotton, despite escalating irrigation pumping costs.

The expansion of cotton into thermally limited environments (where limited available water restricts corn production) may be accompanied by increased adoption of subsurface drip irrigation (SDI) due to, among other factors, the potential for warmer soil temperatures (by reduced evaporative cooling) and hence earlier crop establishment relative to LEPA or spray irrigation (Colaizzi *et al.*, 2006). However, the choice of SDI over spray or LEPA may not necessarily result in less irrigation demand. Bordovsky *et al.* (2006) showed that cotton production with SDI had greater profit potential by concentrating irrigation water and other resources in a smaller land area with the goal of achieving maximum yield per area, rather than allocating resources to a greater land area with the goal of maximizing total farm production. This was partially due to the high initial capital investment of SDI. This behavior was supported by Agri-Partners data, where $FIR_{AP,SDI}$ was 1.01: nearly identical to the $FIR_{AP,CP}$ of 1.03 (Table VI). On the other hand, it is conceivable that unstable commodity and energy prices could shift economic incentives back toward spreading water and other inputs to a greater land area, or reducing inputs to a given area of land due to diminishing returns (i.e., deficit irrigation).

SUMMARY AND CONCLUSIONS

A brief history of irrigation in the Texas High Plains was presented. Total irrigated area reached a peak in 1974 of 2.42 million ha, declining to 1.59 million ha in 1989, and increasing to 1.87 million ha by 2000, slightly greater than the 1.83 million ha irrigated in 1958. By 2000, centre pivots comprised about 72% of the irrigated area. SDI is being increasingly adopted by cotton producers, with some estimates as high as 100 000 ha (about 5%) by 2004. Total irrigation volume pumped tended to parallel irrigated area, reaching a maximum and minimum in 1974 and 1989, respectively, with 2004 estimates ($7.4 \text{ billion m}^3 \text{ yr}^{-1}$) being slightly greater than those of 1958 ($6.4 \text{ billion m}^3 \text{ yr}^{-1}$).

Nearly all irrigation was developed by pumping groundwater from the Ogallala Aquifer, as surface waters are inadequate for this purpose. Ogallala reserves are declining because withdrawals (over 90% are for irrigation) have

exceeded recharge, resulting in declining well yields. The number of irrigation wells has more than doubled between 1958 (48 000) and 2000 (101 000) in order to meet irrigation demand. Most irrigation demand is for grain corn (27%), cotton (35%), grain sorghum (8%), and winter wheat (17%). Most cotton is concentrated in the Southern portion of the Texas High Plains, with the other three crops distributed in the Northern portion.

Several strategies for reducing irrigation demand without impacting irrigation area or crop production levels were discussed. These included increasing the adoption of the Texas High Plains Evapotranspiration Network for irrigation management, converting the remaining gravity-irrigated land to centre pivot, and implementing a corn-to-cotton crop conversion in the Northern Texas High Plains. The Texas High Plains Evapotranspiration Network was estimated to influence about 40% of the irrigated land. If this was doubled to 80% (and gravity-irrigated land area reduced to 10%), irrigation demand was computed to be reduced by 14%. If 50% of the corn irrigated in the Northern Texas High Plains was converted to cotton, an additional 8% reduction in pumping may be possible.

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